

# Large-scale tidal fields on primordial density peaks ?

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## ABSTRACT

We calculate the strength of the tidal field produced by the large-scale density field acting on primordial density perturbations in power law models. By analysing changes in the orientation of the deformation tensor, resulted from smoothing the density field on different mass scales, we show that the large-scale tidal field can strongly affect the morphology and orientation of density peaks. The measure of the strength of the tidal field is performed as a function of the distance to the peak and of the spectral index. We detected evidence that two populations of perturbations seems to coexist; one, with a misalignment between the main axes of their inertia and deformation tensors. This would lead to the angular momentum acquisition and morphological changes. For the second population, the perturbations are found nearly aligned in the direction of the tidal field, which would imprint them low angular momentum and which would allow an alignment of structures as those reported between clusters of galaxies in filaments, and between galaxies in clusters. Evidence is presented that the correlation between the orientation of perturbations and the large-scale density field could be a common property of Gaussian density fields with spectral indexes  $n < 0$ . We argue that alignment of structures can be used to probe the flatness of the spectrum on large scales but it cannot determine the exact value of the spectral index.

*Subject headings:* Galaxies: Clusters: Alignments: Gaussian Random Fields-tides

## 1. Introduction

At the structure formation, density perturbations gravitationally interacted and were subject to the influence of tidal fields. which are generated by the anisotropic distribution of neighbouring perturbations. The evolution and response of density peaks to the tidal field mainly depends on i) the shape of the perturbation, ii) the strength of the external tidal field and iii) the relative orientation between the shape and the field. Concerning shapes, Peacock and Heavens (1985), Bardeen et al. (1986) and González (1994) have confirmed the intrinsic triaxial morphology of peaks in Gaussian random fields. The tidal field, then, get coupled with the quadrupole momentum of the perturbation, exerting a torque and imprinting it angular momentum. The torque per unit mass at a distance  $R$  from the perturbing body decreases as  $R^{-3}$ , but increases proportionally to the mass. If the power spectrum of perturbations is flat on large scales (Vogeley et al., 1992), then this mass increases as  $R^3$  and therefore a divergence in the total torque could in principle appear. This would mean that the local properties of density fluctuations can be affected by the large-scale density field (see also Barnes, 1992). We study this possibility.

The orientation of incipient perturbations is also of great importance because it is closely related to the amount of angular momentum to be acquired. Density perturbation which are born with their major axes aligned with those of the tidal tensor experience a null or weak torque, and therefore would acquire a low amount of angular momentum. It is possible, in principle, that some of these perturbations preserve their initial orientations even after the non-linear evolution of the density field. Whether the initial number of these peaks is statistically significant or not is a subject which has not been studied so far. There are some observational and theoretical evidences which suggest that this number could be important in the past and is preserved today.

Interesting results in the above direction are the analysis of the relative orientation

between the major axes of galaxies and that of their host cluster (e.g. Adams, Strom and Strom, 1986 ) and the orientation between clusters (West 1989, Plionis et al. 1992, Plionis 1994). For example, Lambas, Groth and Peebles (1988, LGP) studied the orientation of galaxies relative to the large-scale structures in which they are embedded (see also Djorgovski 1983, 1986). Not only an important tendency of the mayor axes of galaxies to be aligned with their host larger structures was detected, extending up to  $\sim 4-5h^{-1}\text{Mpc}$ , but also this effect was found morphological type dependent: alignments were detected for elliptical galaxies but not for spirals. In the explanation of the origin of the anisotropy in the orientation of galaxies, LGP discounted the action of the tidal field produced by neighbouring galaxies. They argue that if tidal fields were responsables for the alignment of galaxies, then the same degree of alignment of spirals and ellipticals would be expected. Or alternatively, a correlation would be expected between the orientation of a galaxy and its closest neighbour, independently of their morphological type: none of these tendencies was observed. Moreover, in the N-body simulations carried on by Barnes and Efstathiou (1987), they found that the alignment of the major axes of the formed objects is more prominent than is the alignment of angular momentum vectors of nearby objects. As pointed out by Barnes and Efstathiou (1987) “*The most striking effect seen in these tests is the tendency for nearby objects to point at each other. It seems likely that objects are born with these orientations; if they had been formed with random major axes and sheared into line by tidal torques, we would expect a strong spin-vector versus separation-vector effect, which we do not find*”. If tidal torques between neighbouring structures have not been a determining factor in the generation of alignments, then how do these coherent patterns arise ? Furthermore, LGP have also suggested that *the orientation of ellipticals galaxies could reflects the primordial orientation of maxima of the density field. In such a case, the angular momentum vector of spiral galaxies need not have any connection with the orientation of elliptical galaxies.* The density peaks from which ellipticals form would be oriented in the direction imposed by the large-scale density

perturbations to which they belong. This idea has also been suggested several times by Bond (1986, 1987a,b) to explain the parallel orientation of cD galaxies with the cluster major axes. In a similar direction West (1994) proposed that cD’s formed from special seeds and orientations.

It is precisely the primordial tidal field and the primordial alignment of density perturbations which we will investigate in this paper. In Sect. 2 the influence of the far density field on the local properties of galactic and cluster scale peaks are studied, as a function of the distance and the spectral index of the density field; in Sect. 3 a measure of the strength of the tidal shear is carried on by considering two methods; in Sect 4 a discussion of the results and their possible consequences is presented.

## **2. Is there any correlation between the large and small-scale density field ?**

### **2.1. Basic Formalism and Procedure**

Properties such as the amplitude, the shape, the orientation and the strength of the deformation tensor of density peaks are determined by the superposition of density waves. One way of quantifying the influence coming from the large-scale field on galactic-scale peaks, consists in measuring changes of these properties as the density field is smoothed on increasing mass scales  $M = M(R_f)$ . Where the only physical consequence of using a larger radius of filtering,  $R_f$ , is the generation of more massive perturbations of a larger characteristic radii. Once the primordial density field is generated within a  $64^3$  cubic grid, and smoothed with a Gaussian filter function, the peaks mass grows as (e.g., Bardeen et. al. 1986)

$$M(R_f) = (2\pi)^{3/2} \bar{\rho} R_f^3 = 4.37 \times 10^{12} R_f^3 h^{-1} M_{\odot}. \quad (1)$$

A radius of  $R_f^{(1)} \approx 0.6\text{Mpc} \equiv 1$  corresponds with a galactic mass scale  $M \approx 10^{12}M_\odot$ . For rich clusters,  $R_f^{(1)} \approx 10\text{Mpc} \equiv 1$  yields  $M \approx 10^{15}M_\odot$ . Next, we identify the positions  $\mathbf{x}_i$  of the density peaks. Suppose now, that the density field is smoothed on a larger scale by using  $R_f^{(2)} = 2(\approx 1.3\text{Mpc})$ . If changes in the properties of the peaks at the positions  $\mathbf{x}_i$  are observed, then they can be attributed to the remaining superposition of density waves bounded by the spherical shell defined by the difference  $\Delta R_f = R_f^{(2)} - R_f^{(1)}$ . Intuitively, one expect that when  $R_f^{(2)} \approx R_f^{(1)}$ , the general properties of a given density peak do not change considerably. The more distant shells are specified by taking two consecutive filtering scales as  $R_f^{(i+1)} - R_f^{(i)}$ . The filtering  $R_f^{(8)}$  represents the largest scale of 4.8Mpc when we analyze the effect on galactic-scale peaks, and 80Mpc when we analyze the effects on cluster-scale peaks. Throughout this paper we consider an Einstein-de Sitter ( $\Omega = 1$ ) Universe.

In the present analysis we restrict ourselves to quantify the changes in i) the amplitude of the perturbations and ii) the changes in orientation and strength of the their deformation tensor. Thus, for  $R_f^{(1)}$  and a given perturbation, we shall evaluate the angle  $\theta$  subtended by the major axes associated with the unperturbed and the perturbed deformation tensor, this latter being the result of increasing the smoothing scale. If no changes are observed, it would be indicative that the density waves of very long wavelength have not important effect on the galactic-scale peaks. The deformation tensor is calculated from the Zel'dovich (1970) approximation as

$$\mathbf{D}_{jk} = \delta_j k + b(t) \frac{\partial v_k}{\partial q_j}, \quad (2)$$

where the values of the density and the velocity field at points outside the grid vertexes are obtained by interpolation. The validity of the computed peculiar velocity is checked out through the continuity equation (Peebles 1980). Finally, before going on into the results, we shall remark that the discussion will be addressed to power law spectra,  $P(k) \propto k^n$ , with  $n = 1, 0, -1, -2$ . The spectrum for the Cold and Mixed Dark Matter models can be fitted through a power law with some appropriate index. For instance, the predicted shape of

the CDM fluctuations spectrum corresponds with  $P(k) \propto k^{-3} - k^{-2}$  on subgalactic and galactic scales, and  $P(k) \propto k^{-1} - k^0$  on the scale of rich clusters and superclusters (Bond and Efstathiou 1984; West 1994).

## 2.2. Results

Figure 1 is an example of the changes produced in the relative orientation of the deformation tensor for some of the highest peaks. Meanwhile, the sequence of histograms of Figure 2 shows the total number of peaks  $N_{pk}$  with changes in  $\cos\theta$  as a function of the mass scale. It is observed that the nearest shells produce the most important changes in the orientation of the deformation tensor as can be deduced from the changes produced in the form of the histograms. The influence on the peaks decreases with the distance of the shell of mass considered. When distant shells, and therefore the large-scale density field, are taken into account the form of the histograms remains unaltered for the steeper spectra, but not so for the flatter ones. To clarify this point, consider the form of the histograms for the cases  $n = 1, 0$ . The maximum of the distributions of peaks lies close to  $\cos\theta = 1$ , corresponding with small changes in the orientation of the deformation tensor. For these spectral indexes, the number of peaks within the interval  $0 < \cos\theta < 0.9$ , for which the orientation changes are larger than  $\sim 25^\circ$ , includes approximately 60 – 70% of the total sample for  $R_f^{(2)} - R_f^{(1)} \approx 1.6\text{Mpc}$  and decreases to 20 – 30% for  $R_f^{(3)} - R_f^{(2)} \approx 2.4\text{Mpc}$ . This means that effects on density peaks are mainly due to the neighbouring distribution of mass to this scale.

For flat spectra,  $n = -1, -2$ , the situation is different. The form of the initial distributions for the nearest shell, is modified as one considers larger filtering scales. The peak of the histograms becomes sharper near  $\cos\theta = 1$  only to scales larger than  $\approx 3\text{Mpc}$ . A large number of peaks present changes in the orientation of the deformation tensor even for

shell distances of  $\approx 3 - 5\text{Mpc}$ . Such scales nearly matches the scale of a cluster of galaxies. Thus, a correlation between a cluster-scale perturbation and its central regions would be feasible. The numerical simulations by Faber (1982), Blumenthal et al. (1984) and White & Frenk (1991) suggest that a power spectrum index of  $n \approx -2$  is consistent with observed galaxy properties. If we identify galaxies in a one-to-one mapping with peaks in the density field, our results would suggest that the orientation of the deformation tensor for galactic-scale perturbations is correlated with the surrounding mass on scale of the parent cluster. Furthermore, the observational study by Vogeley et al. (1992) and Einasto et al. (1993) have estimated the shape of the fluctuations spectrum on scales of  $\sim 20 - 100\text{Mpc}$ , finding a spectral index  $n \approx -1.5 \pm 0.5$ . Which brings as a possible consequence that the degree of correlation observed in Figure 2, for flat spectra, suggests that a correlation of clusters with larger scales should be present.

To analyse whether this correlation is applicable to the orientation of peaks, we calculated the relative orientation between the main axes of the deformation tensor and those of the inertia tensor for  $R_f^{(1)} = 0.6\text{ Mpc}$ . Figure 3 displays the distribution of relative orientation as a function of the spectral index. These distributions show that there is an important fraction of the peaks whose tensors are similarly oriented;  $\sim 30 - 50\%$  of the whole sample for  $n = -1$  and  $n = -2$ , and approximately  $20 - 30\%$  for  $n = 1$  and  $n = 0$ . The misalignment of the main axes of the two tensor, would have as a consequence that the final morphology of the structures formed from the collapse of perturbations, will be poorly correlated with the initial shape of their progenitors. It is partially due to this misalignment that the perturbations will acquire angular momentum with no correlation between neighboring galaxies. Because the magnitude of the changes in the orientation of the deformation tensor are related to the distribution of mass on larger-scales, the degree of misalignment with the inertia tensor increases. So can happen with the angular momentum acquisition. Thus, the tidal shear effects produced by the large-scale density field will affect the evolution of peaks depending



on how they are initially oriented with the tidal field.

### 3. Effect produced by the surrounding density field

So far, we have analysed the changes in the orientation of the principal axes of the deformation tensor without paying attention in the magnitude of the deformation itself. We now assess such magnitudes in order to estimate the importance of the tidal effects produced on the peaks by the surrounding mass distribution. This will tell us from which scales the most important contribution to the deformation tensors is being produced.

#### 3.1. Changes in the density contrast

We first estimate the tidal field effects on the deformation tensor of peaks through the equation which relates the eigenvalues  $\lambda_i$  of the deformation tensor to the density contrast as

$$\sum_{i=1}^3 \lambda_i^{(j)} \propto \delta^{(j)}, \quad (3)$$

where  $j$  denotes the values corresponding to different mass scales. The difference of these

$$\sum_{i=1}^3 \lambda_i \equiv \sum_{i=1}^3 (\lambda_i^{(j+1)} - \lambda_i^{(j)}) \propto \delta^{(j+1)} - \delta^{(j)}, \quad (4)$$

shall provides us a measure of the strength of the effect produced by the external field. Figure 4 shows the distribution of peaks as a function of the difference of the eigenvalues,  $\sum \lambda_i$ . The high number of peaks at  $\sum \lambda_i \approx 0$  indicates a weak influence of the nearest mass distribution on the deformation tensor by the fact that the eigenvalues remain unperturbed. This general behaviour is observed for all the spectral indexes. By comparing the changes in the shape of the initial distributions of peaks, as the filtering scale increases, it is observed that no important correlation exists in the cases  $n = 1$  and  $n = 0$ . However, for flat spectra,

the initial shape of the distribution is slightly modified up to scales of  $\Delta R_f \approx 4 - 5 \approx 4\text{Mpc}$ . After these scales the effect decreases significantly as shown by the high number of peaks distributed around  $\sum \lambda_i \approx 0$ . This suggests again an influence of the large-scale superposition of density waves on the peaks. On scales of clusters of galaxies, the values  $R_f \approx 4 - 5$  would correspond to a correlation of cluster-scale perturbation with their environment on scales of  $\approx 30 - 40\text{Mpc}$ .

### 3.2. Strenght of the tidal field

We now provide a measure of the changes produced on the deformation tensor, by resorting to a concept widely used in the theory of matrix perturbation: the norm of the perturbation matrix (e.g. Stewart and Sun, 1990). Roughly, the goal of this theory is to predict, or bound, the changes in physical processes described by a matrix when the elements of the matrix change. The theory would assess, for example, how far the 'magnitude' of a matrix associated to a physical process –e.g. the deformation tensor  $\mathbf{D}_{ij}^{(1)}$ – will change when the elements of the matrix change as  $\mathbf{D}_{ij}^{(2)} = \mathbf{D}_{ij}^{(1)} + \Delta_{ij}$ , due to a perturbation,  $\Delta_{ij}$ . The prerequisite for answering this question is to make precise the term 'magnitude', which is done by defining a norm in the space of matrixes. We adopted the Frobenius norm defined as

$$\mathbf{F} \equiv \|\Delta_{ij}\| \equiv \sqrt{\sum_{i,j} |\alpha_{ij}|^2} \equiv \sqrt{\sum_i \lambda_i^2}. \quad (5)$$

When the deformation tensor does not suffer important changes the norm will tend to take small values. The lower limit correspond to  $\mathbf{F} = 0$  in which the elements of the deformation tensor are not affected.

Figure 5 displays the distribution of peaks with norm  $\mathbf{F}$ . A clear difference in the strenght of the tidal field is observed between the different models. The maximum of the distribution of peaks, in the cases  $n = -1$  and  $n = -2$ , shows a considerably deviation from zero at large

radii of filtering, thus confirming the influence of the superposition of the density waves which conform the large-scale perturbations, on the local deformation of small-scale perturbations. This is also seen from Figure 6a, where we plot the mean strength  $F$  as a function of  $R_f$ . The norm of the deformation tensor at  $R_f^{(1)}$  was used to normalize the maximum effect to unity. We confirmed our prior results: steep spectra show a correlation only with the nearest distribution of mass on scales smaller than  $R_f = 2$ . Flat spectra show important effects coming from even larger-scales. An insight of the decaying rate of the effect on density peaks is provided by the difference of  $F$ 's between different shells, which we binned as

$$\Delta F_i = | F(R_f = 8/i) - F(R_f = 4/i) |, \quad \text{for } i = 4, 2, 1 \quad (6)$$

showed in Figure 6b. It is observed a general tendency for the influence to decay. However, the rate of decaying is faster for those models with steep spectra. From these results, one can see that there is no a divergency due to the mass increasing in the density field. However, it keeps producing important effects on small-scale peaks.

### 3.3. Density peaks and their environment ?

One can expect that the alignment of peaks to show up if the orientations of the peaks are compared with the orientation of their host larger fluctuations. Thus, we have explored the possibility of parallel alignments by calculating the cosine of the angle subtended by the main axes of the inertia tensor of galactic-scale peaks and the major axes of the inertia tensor of the larger-scale fluctuation.

The small-scale peaks ( $R_f \equiv 1$ ) used in this analysis were those located within a sphere of radius  $R_f \equiv 8$ , and whose typical number was  $\sim 40$  peaks within this region. 10 cases were analysed for each of our 6 realizations of a spectrum with  $n = -2$ . Some of the results are presented in Figure 7. A weak parallel alignment was detected in six cases as those

marked as [3] and [6]. Each of these include  $\approx 28\%$  of the total number of peaks. However, we could not get any clear insight about the ultimate reason of their alignment (e.g. highest peaks, ellipticity, number of neighbours), as for allowing us to reproduce them with a major statistical weight in a larger realization. What is noteworthy is the existence of some cases for which alignment exist.

The even weaker trend for parallel alignments showed by the other cases –which include at most 10% of the peaks– is probably not too surprising since we carried out the comparison of the orientations with peaks on a scale larger than that where we found evidence of a stronger correlation,  $\Delta R_f \approx 4 - 5$ . These results therefore, are useful as indicators of an upper limit at which we could expect primordial alignments effects. If one adopts a cluster-scale smoothing of the density field, the present results would suggest us that we cannot expect alignment of the cluster-cluster type on scales larger than  $40 - 60h^{-1}\text{Mpc}$ , in agreement with some observational results: an alignment of the main axes of clusters of galaxies has been detected up to scales of  $30 - 60h^{-1}\text{Mpc}$  (e.g. Binggeli 1982; Oort 1984; Plionis 1994) and even at the central regions of clusters between the cD galaxy and their host cluster (Rhee et al., 1990; West, 1994).

For the steep spectra, the distributions showed no signals for any kind of alignment. The density peaks orientations are uniformly distributed.

We have also found that the inertia tensor of about 10 – 15% of the density peaks is oriented with the main axes of the large-scale perturbations on scales smaller than  $\Delta R_f \approx 8$ . Then, one should expect that at the moment of collapse the inner regions would already be aligned with the host structure. The primordial tidal field acting on these perturbations will not significantly change their initial orientations because the quadrupole term of the peaks, which is the first in getting coupled with the tidal field, would be already oriented in that direction.

#### 4. Discussion

We have explored the possibility of the existence of primordial alignment effects which could survive the non-linear evolution of the density field. Some evidence was detected that such alignments do exist and can be the progenitors of the coherence in the orientation of galaxies in clusters and between clusters. The scales we found, to which the large-scale density fluctuations affect the small-scale peaks, nearly match those to which alignment of structures have been reported both from observational studies (e.g. Binggeli, 1982; Oort, 1984; Plionis, 1994; LPG 1987; Muriel and Lambas, 1992) and from numerical simulations (e.g. Dekel, West and Aarseth, 1984; Barnes and Efstathiou, 1987; West, 1989; Little, Weimberg and Park, 1991). These scales are  $\approx 3 - 5h^{-1}\text{Mpc}$  for alignment of galaxies and  $\approx 30 - 50h^{-1}\text{Mpc}$  for clusters of galaxies.

The weak evidence of alignments we found resulted valid only for flat spectra, and therefore a observational confirmation of alignments to significant statistical levels could be used as an evidence of the flatness of the spectrum at the scales observed, but it cannot determine the exact value of the spectral index.

A natural consequence for the significant fraction of peaks with a misalignment between the inertia and the deformation tensors, is that they are expected not only to acquire angular momentum but also to suffer important morphological changes depending on the strength of the tidal field. A question which arise from the misalignment is wheter it is the shape of the peaks or it is the deformation tensor which determine the way in which the peak collapse. If the latter is the dominant mechanism, perturbations will be able to acquire angular momentum from the large scale density field, without being correlated with their nearest neighbours.

A clue on the origin of correlations to different scales was given by Bond (1986, 1987). He showed that for Gaussian random fields, density peaks on scale of clusters have triaxial

tails which can extend to  $\sim 20h^{-1}\text{Mpc}$ . The nonlinear evolution of these density peaks would enhance that initial anisotropy producing that the clusters tend to be born aligned with their surroundings (West, Dekel and Oemler, 1989; West, Villumsen and Dekel, 1991; Barnes, 1992). This probably is the origin of the alignments of neighbouring clusters. An attempt for following the origin and evolution of the alignment of structures is being carried out by González and Colín (1997).

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Fig. 1.— Examples of the changes in the orientation of the main axis of the deformation tensor at the density peaks positions.

Fig. 2.— (a) Histograms of the changes in the orientation of the deformation tensor, as a function of the shells distance, for  $n = 1, 0$ , (b) for  $n = -1$  and (c) for  $n = -2$ .

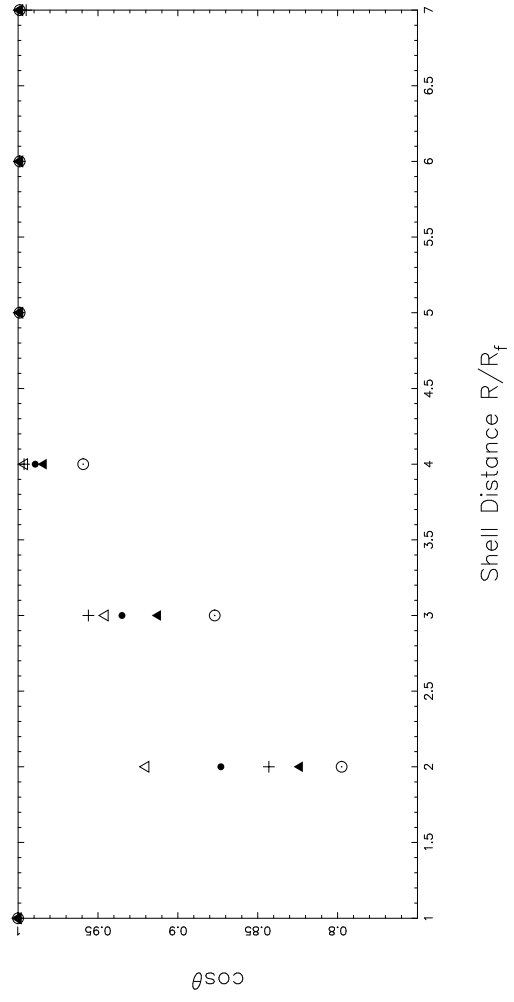
Fig. 3.— Histograms showing the misalignment between the main axes of the deformation tensor and those of the inertia tensor.

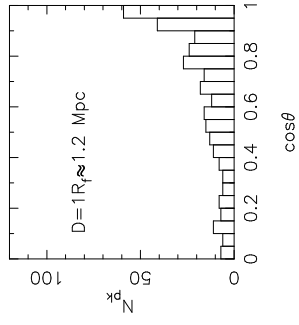
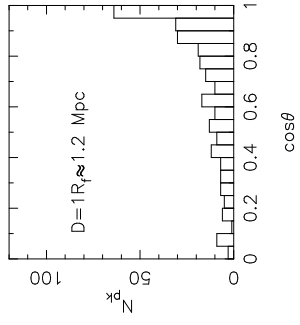
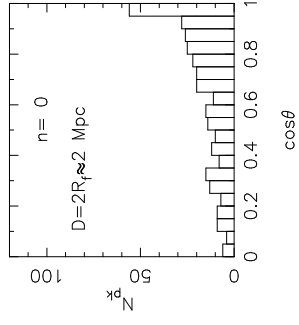
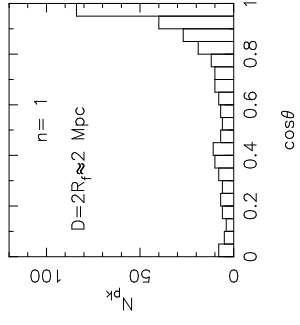
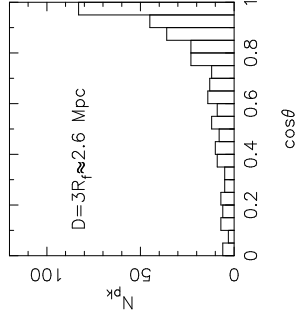
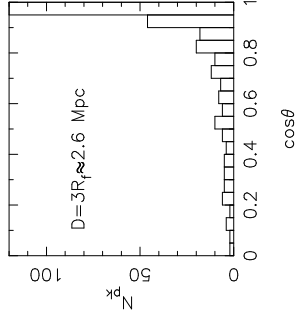
Fig. 4.— Histograms of  $\sum_{i=1}^3 \lambda_i = (\lambda_i^{(j+1)} - \lambda_i^{(j)})$  as a function of the shell distance. The cases  $n = -1, -2$  show important changes at the distances indicated in the panels.

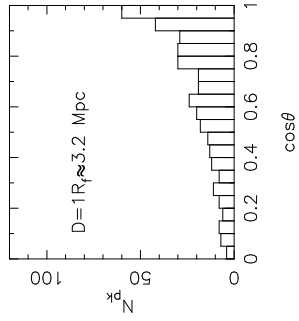
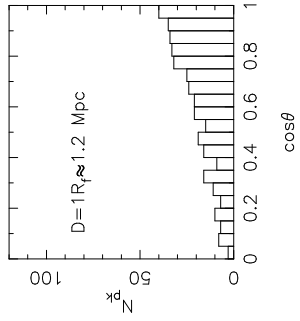
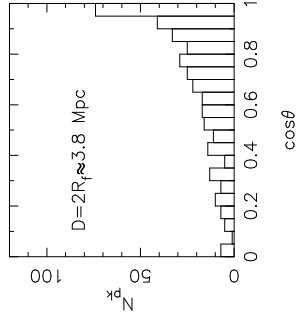
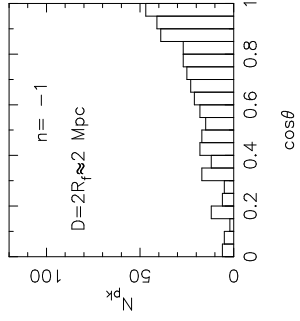
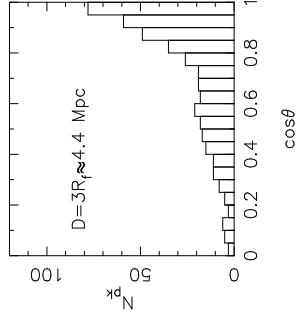
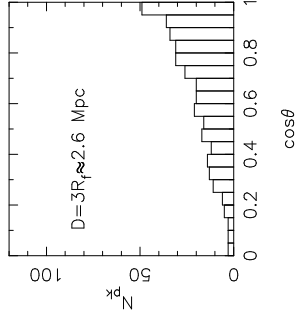
Fig. 5.— Histograms of the Frobenius norm, as a function of the shell distance and the spectral index. For  $n = 0$ ,  $F = 0$  suggest no important changes coming from the scales indicated in the panels.

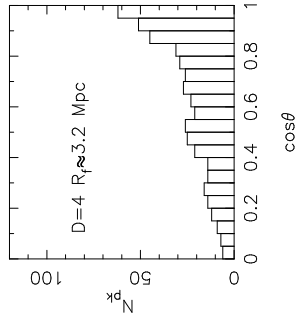
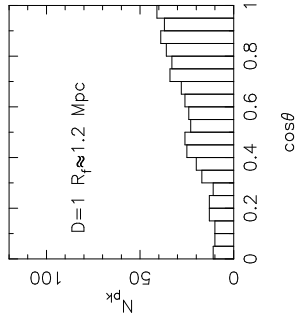
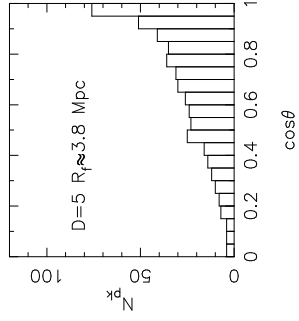
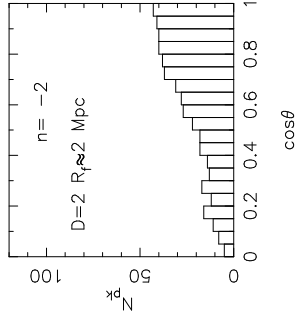
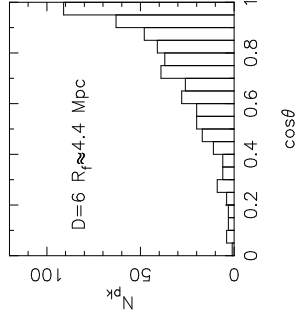
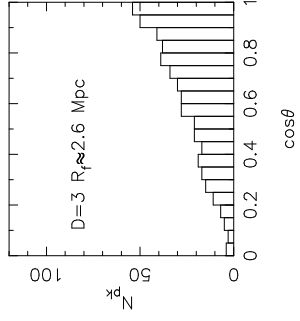
Fig. 6.— (a) Decaying rate of the Frobenius norm as a function of the shell distances. (b) Decaying rate of F when the shell distances are binned as indicated in the text.

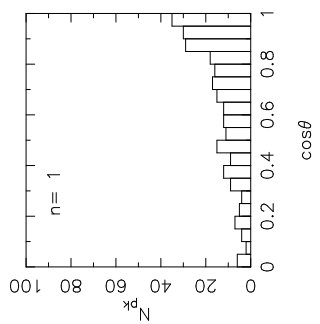
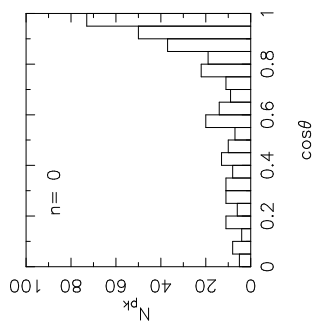
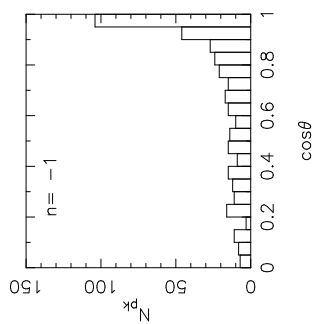
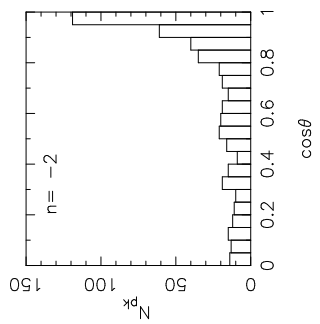
Fig. 7.— “*Clusters of peaks*” showing the orientational distribution of their members. Cases [3] and [6] show a weak tendency for alignment.

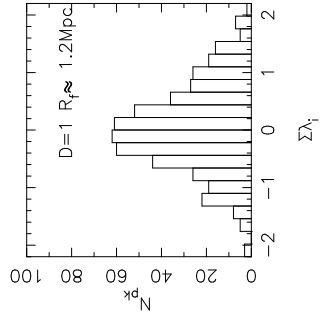
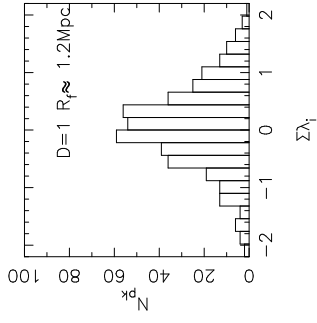
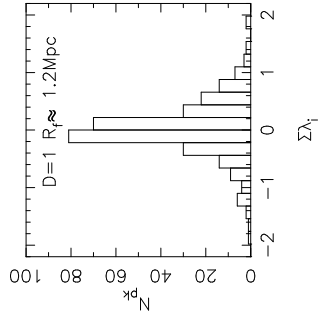
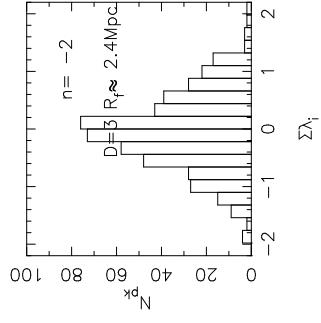
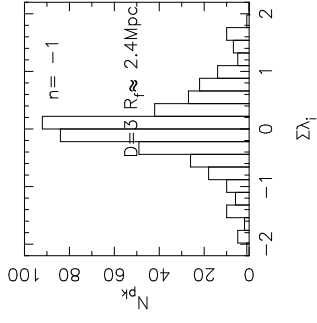
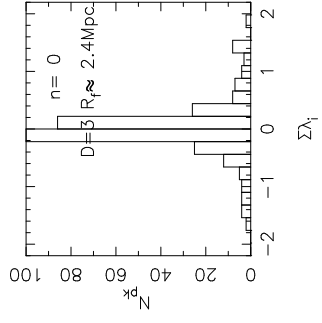
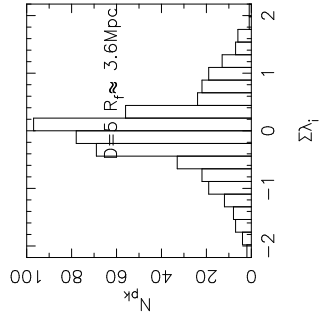
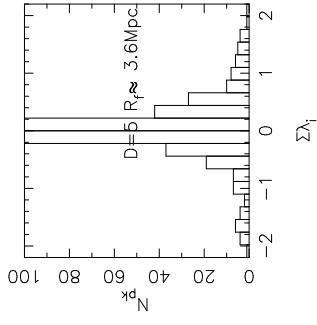
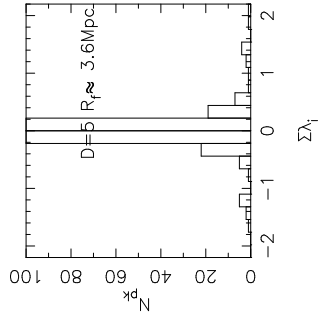




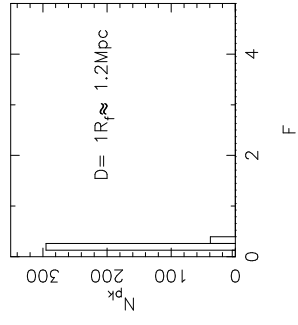
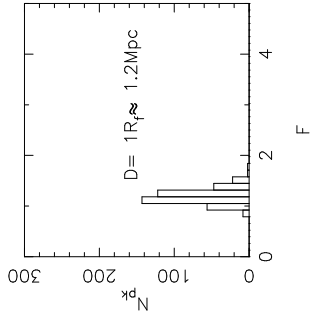
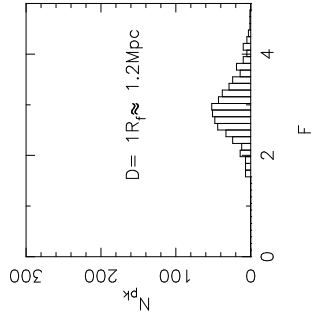
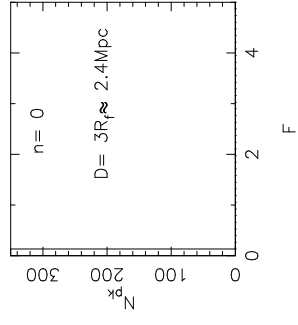
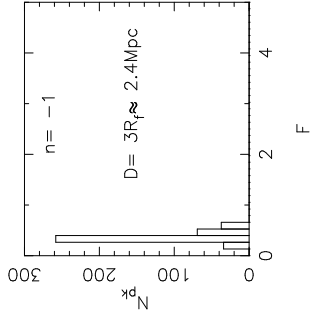
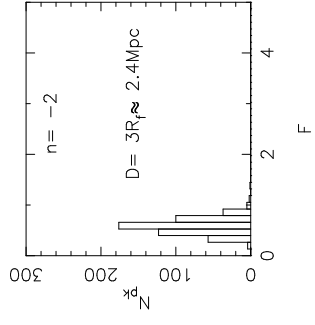
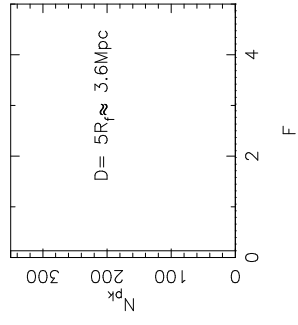
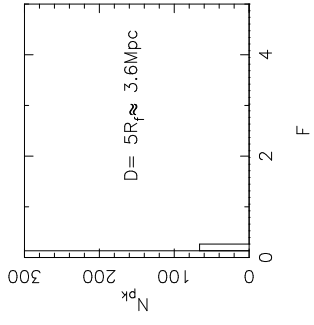
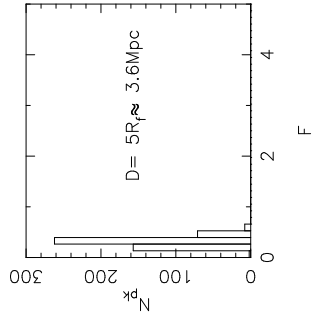




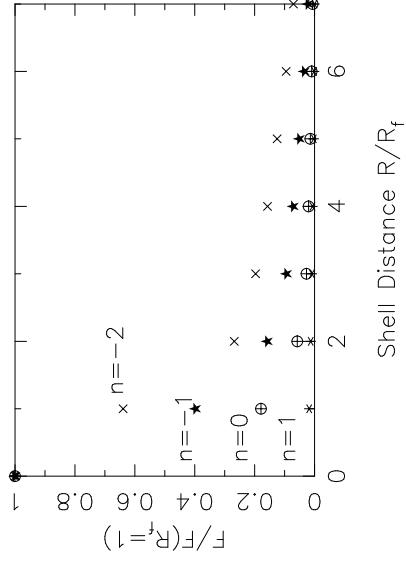








a)



b)

